Synchrotron Radiation & Detectors

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NSLS

Outline

- Properties of synchrotron radiation
- A typical EXAFS beamline
- Monochromators
- Detectors
  - Integrating
  - Photon-counting

Properties of SR from dipole source or wiggler

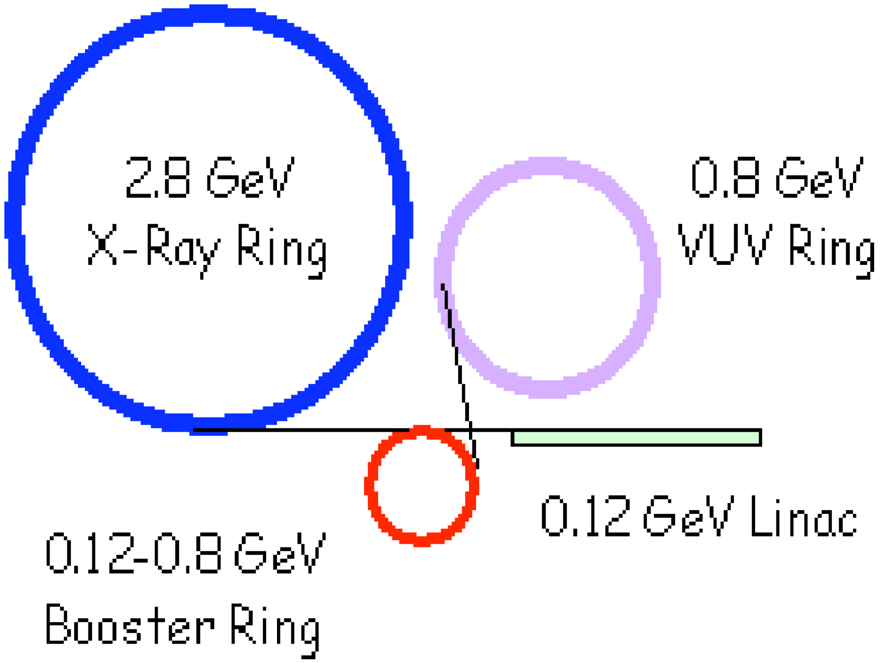
- Continuous spectrum from IR to hard x-ray.
- Intense
- Polarized
- Pulsed
- Collimated

Undulators

- Weak-field, many-pole device
- Pseudo-monochromatic output (dE/E~1/N)
  - usually need to scan undulator gap in order to follow EXAFS monochromator scan. Possible at some facilities.
- Collimated in both directions
- Brighter, but not necessarily more intense.

NSLS accelerators

- Several machines
  - Linac
  - Booster synchrotron
  - VUV storage ring
  - X-ray storage ring.



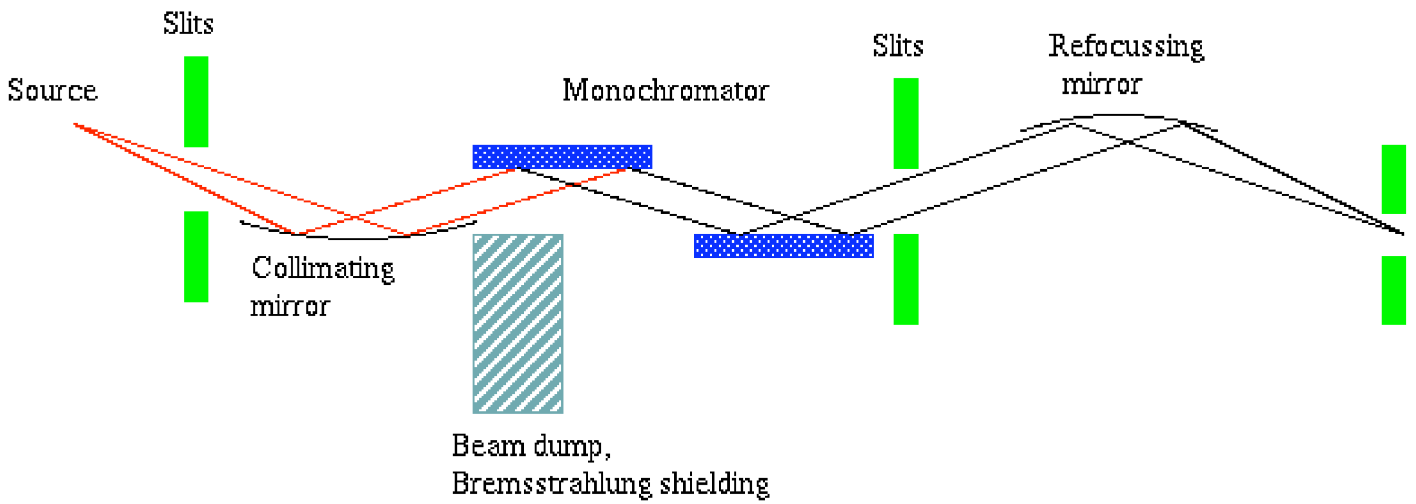
What is a beamline?

- It is the collection of stuff which transports and conditions the photon beam from the SR source to your experiment.
- It typically contains subsystems to tailor the size, angular divergence and spectral properties of the beam to provide efficient coupling to the experiment.
- It also contains monitoring devices to allow alignment of those subsystems.

Beamline components

- Front End
- Windows
- Apertures
- Mirrors (focussing, collimating etc.)
- Monochromators
- Beam monitors (position and/or intensity)
- End-station (sample manipulator, environment control, detectors etc.)

Generic beamline layout

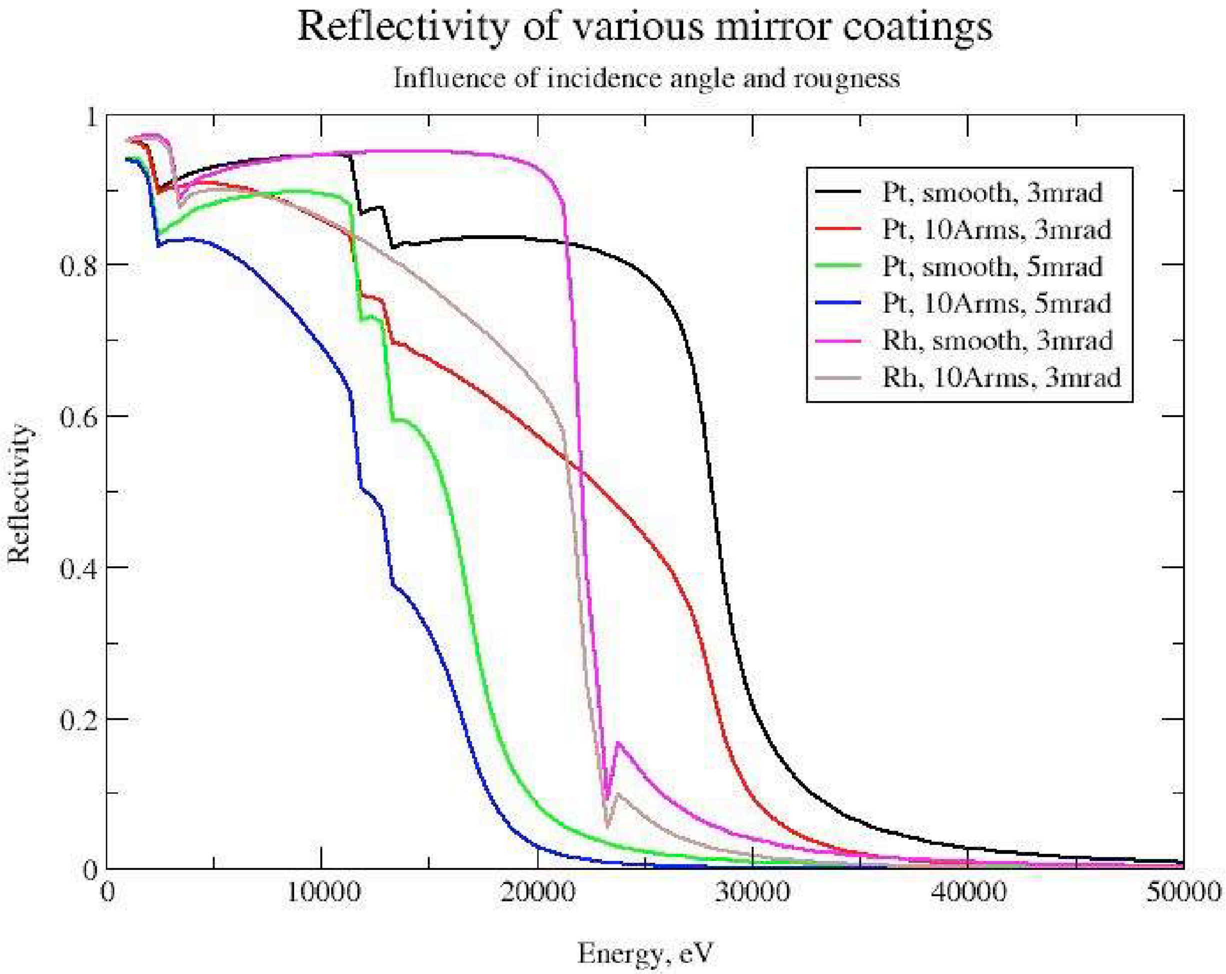


- ❖ Not all beamlines have all components
- ❖ No beam monitoring components are shown.
- ❖ Details depends on source properties and experiment needs.

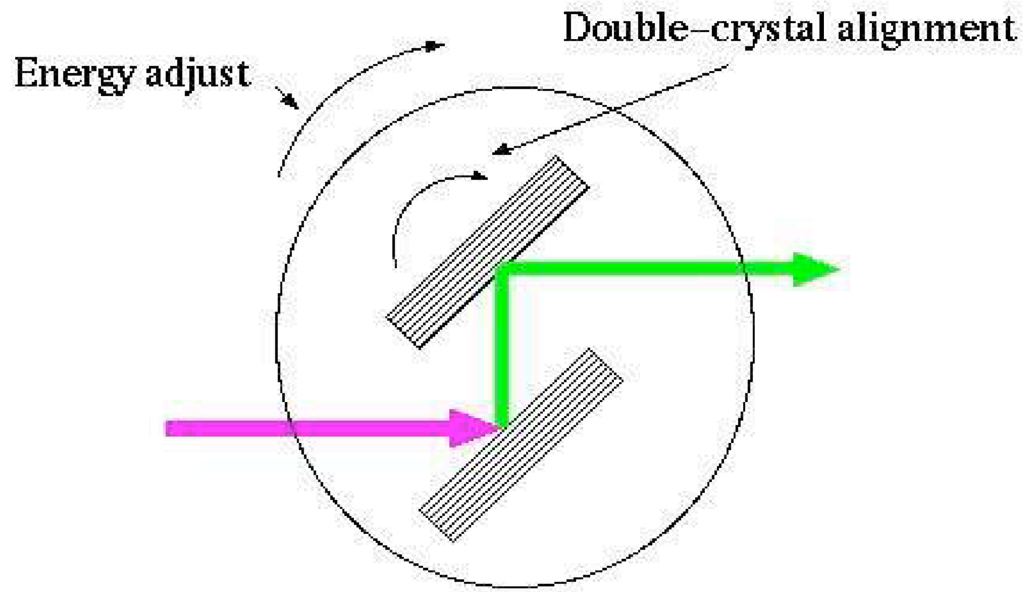
Mirrors

- Mirrors are used as collimators, focusing element and spectral control elements
- The refractive index for x-rays is slightly less than unity
- No normal-incidence mirrors!
- Only extreme grazing incidence works.
- Critical angles for total *external* reflection are in the milliradian range.
- Critical angle depends on material and energy.

Mirror coatings



Double-crystal monochromator

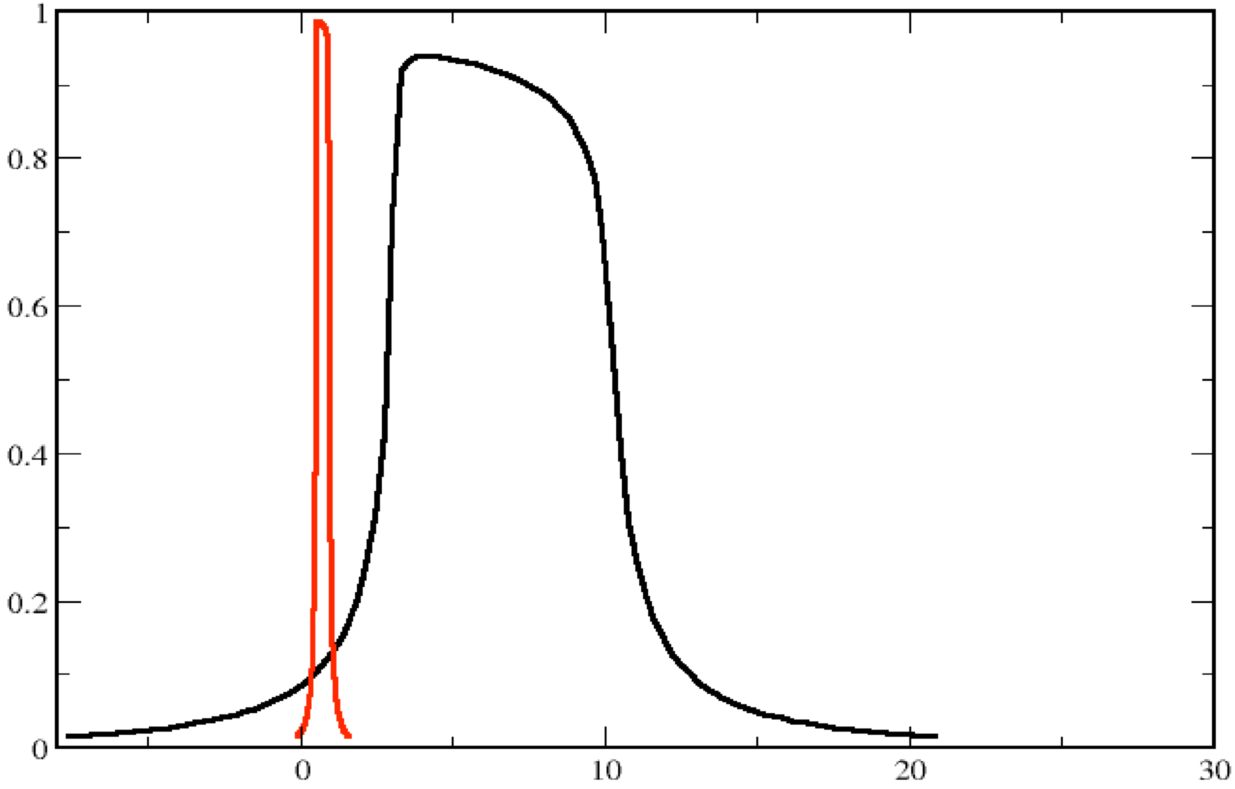


- By far the most common is the 2-crystal Bragg monochromator.
- It uses two consecutive Bragg reflections from identical perfect crystals.
- It only works efficiently if both crystals are highly perfect.

Silicon reflectivity curves

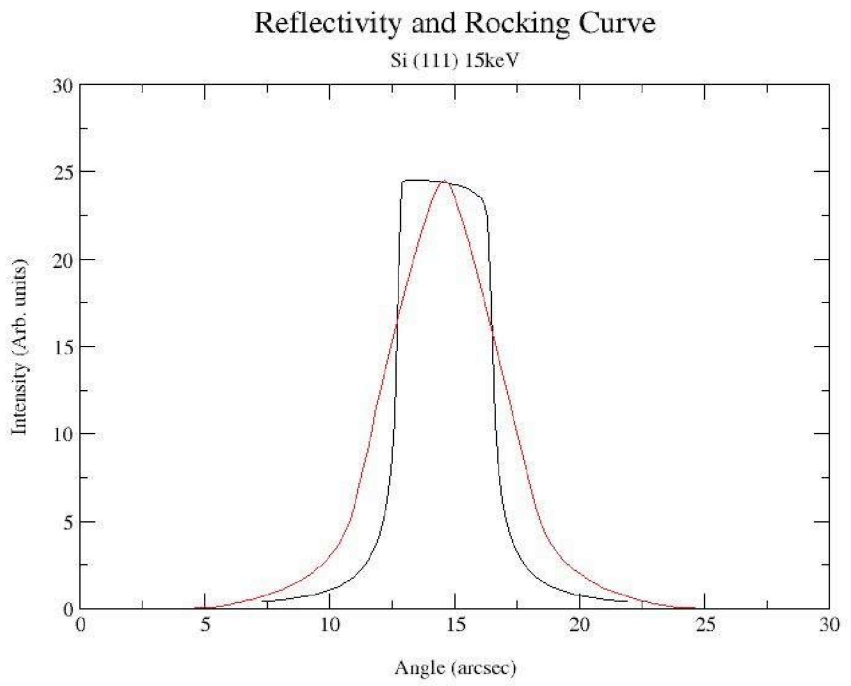
- Width of 'Darwin curve' reflects the strength of the xray-crystal interaction
  - stronger scattering -> wider angular acceptance
    - high-Z -> wider acceptance
    - higher order -> lower angular width
  - Angular width relates to energy resolution
    - dE/E = cot(theta)*delta(theta)
    - delta(theta) can be geometrical or from Darwin width, depending on setup.

Calculated Darwin curves



Rocking curves

- Perfect crystal Bragg reflection curves are very narrow.
- This makes peak adjustment sensitive.
- Mechanical stability requirements are extremely high.
- Separate-crystal mono’s are expensive.



Harmonic rejection

- High-order diffraction can cause spectral contamination and reduce effective absorption coefficient.
- 2-crystal monochromator can reduce this contamination at the expense of some intensity by 'detuning' the crystal parallelism. The high-order rocking curve is much narrower than the fundamental, so its intensity drops faster with detune.
- Proper choice of mirror angle and coating can also help.

Separate crystal design

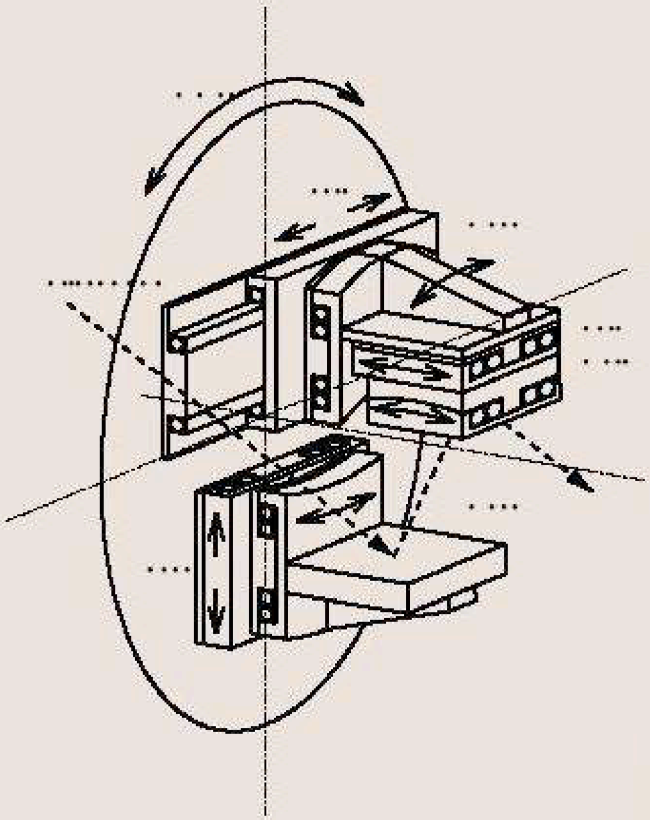
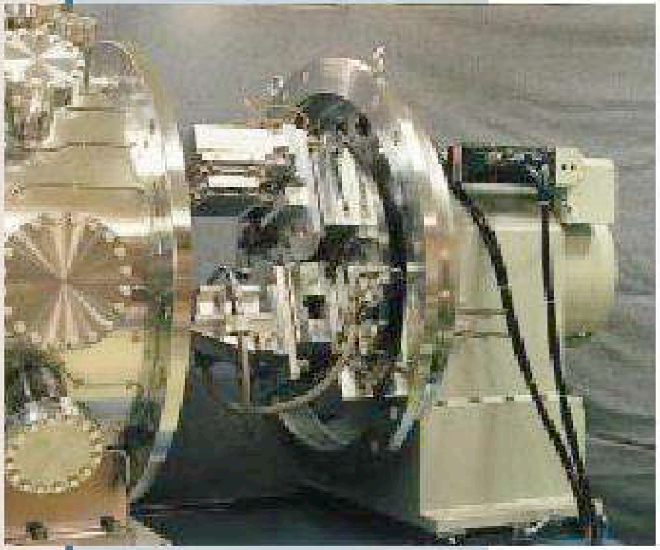
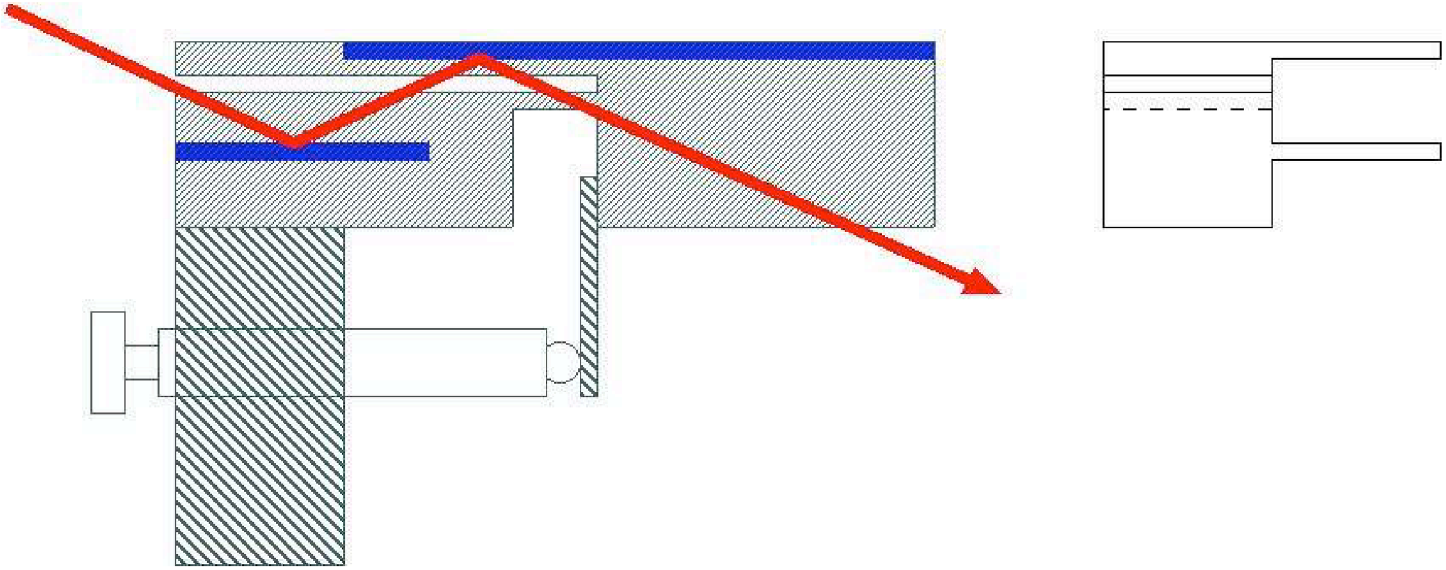


Fig.2. HLD-1 crystal adjustment mechanics.



Crystal adjustment mechanics
of HLD-1 monochromator.

Channel cut crystals



- Machined from solid perfect-crystal block.
- Two crystals are intrinsically aligned.
- Flexure cut in crystal allows elastic deformation of monolith to make fine adjustments to orientation of two reflecting plates.
- Only possible with silicon.

Detectors

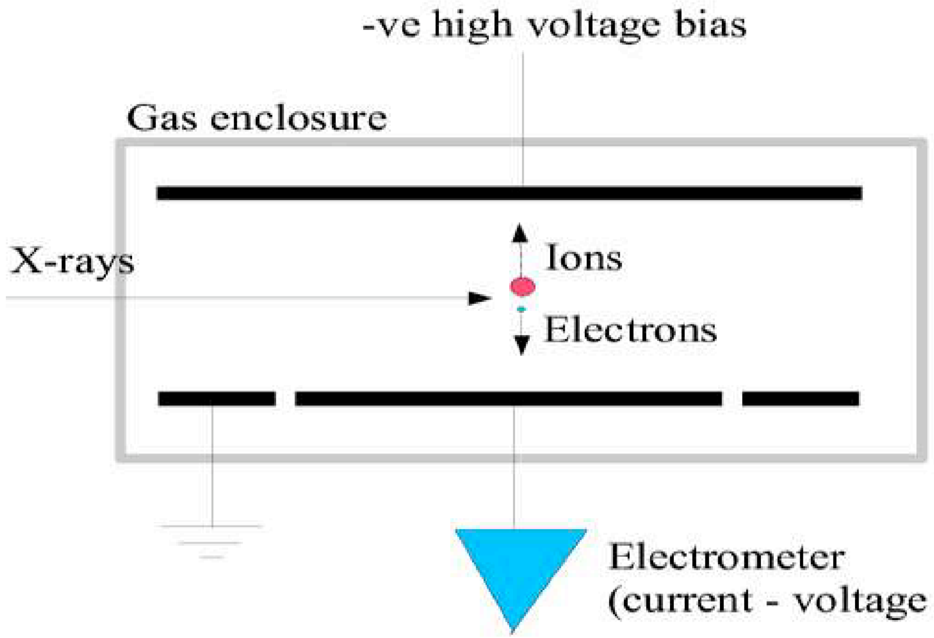
- Only discuss electronic hard x-ray detectors.
- All use same basic principle:
  - X-ray is absorbed by atoms within detector active volume
  - Atom is ionized
  - Electrons and ions are collected by imposing high electric field across collection electrodes.
- Differences come from detector material and readout electronics.

Detector types

- Integrating
  - Ionization chambers
  - PIN diodes
  - PIPS detectors
- Photon counting
  - HPGe detector and similar
  - Gas proportional counter
  - Avalanche photodiode

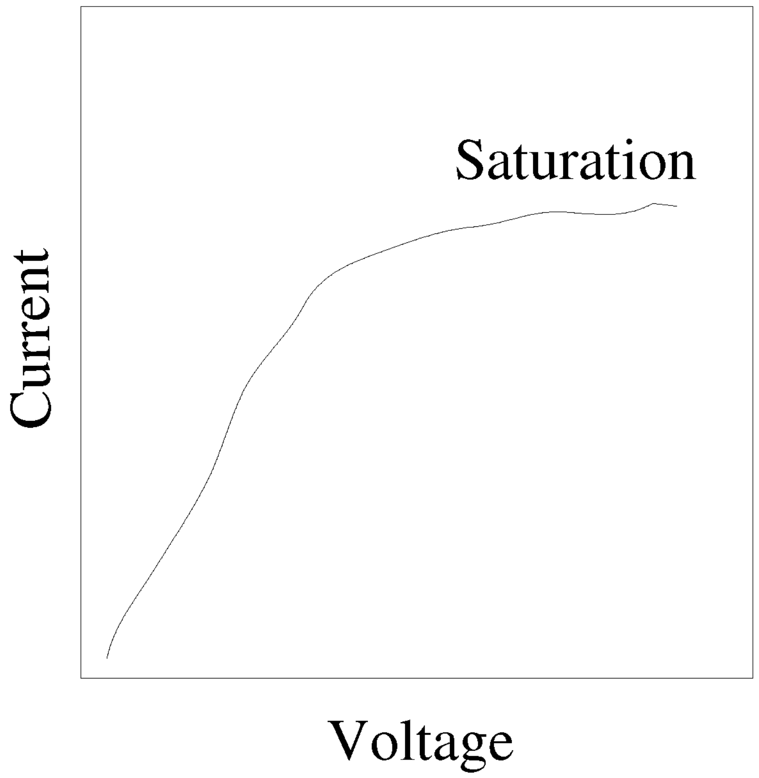
Ionization chamber

- Photon is absorbed by gas atom
- Photoelectron and Auger electrons emitted (ionization)
- These electrons cause more ionization
- High voltage bias across plates causes electrons and ions to drift in opposite directions.
- Charges collected results in current flow which is proportional to incident x-ray intensity.



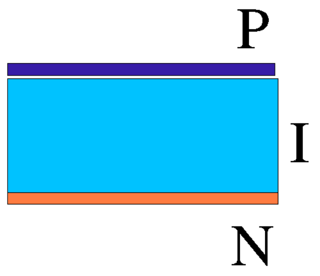
Operating voltage

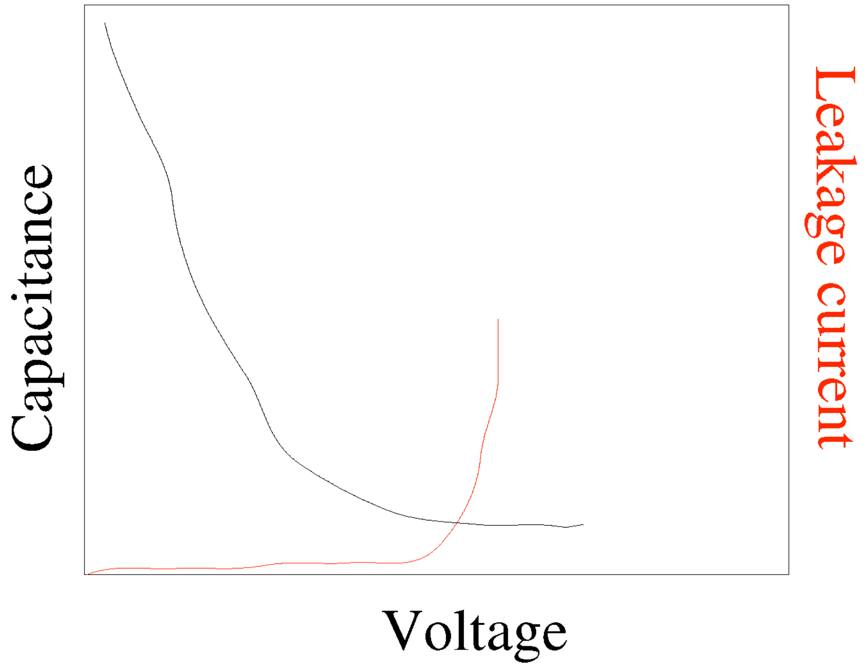
- Electrons and ions like to recombine
- Bias voltage pulls them apart before they can recombine.
- Measured current increases with bias voltage until all charges are collected. This is called 'saturation'.
- Ion chambers should ALWAYS be operated in the saturation region.



Silicon photodiodes

- PIN photodiodes
  - 'solid-state ion chamber'
  - modest area
  - low leakage & capacitance
  - Usually used fully depleted
- PIPS detectors
  - Large area
  - high capacitance
  - relatively high leakage current
    - Usually used at zero bias





Which one to use when?

- Ion chamber can be semi-transparent, so is good for I0 measurement.
- Gas ionization costs 30eV / ion pair compared to 3.6ev for electron-hole production in Silicon.
  - Silicon diodes better for low intensities (e.g. fluorescence detection)
  - Ion chambers good for transmission measurements

Computer interface

- Most common way to measure ion current is electrometer (I -> V) feeding Voltage-frequency converter (V -> F) feeding a pulse counter. This arrangement seems clumsy, but actually works quite well
  - Effective integration time is same for all detectors, integrating and photon-counting
  - long integration time can suppress some noise signals (e.g. 60Hz pickup).
- Needs care to avoid ground loops and nonlinearities
  - Electrometer should be as close as possible to ion chamber
  - Multiple grounding points should be avoided, e.g. through power cord and/or optical table and/or CAMAC or VME crate. This is often difficult to get right.
- Statistical error in measurement is NOT sqrt(N) !!!

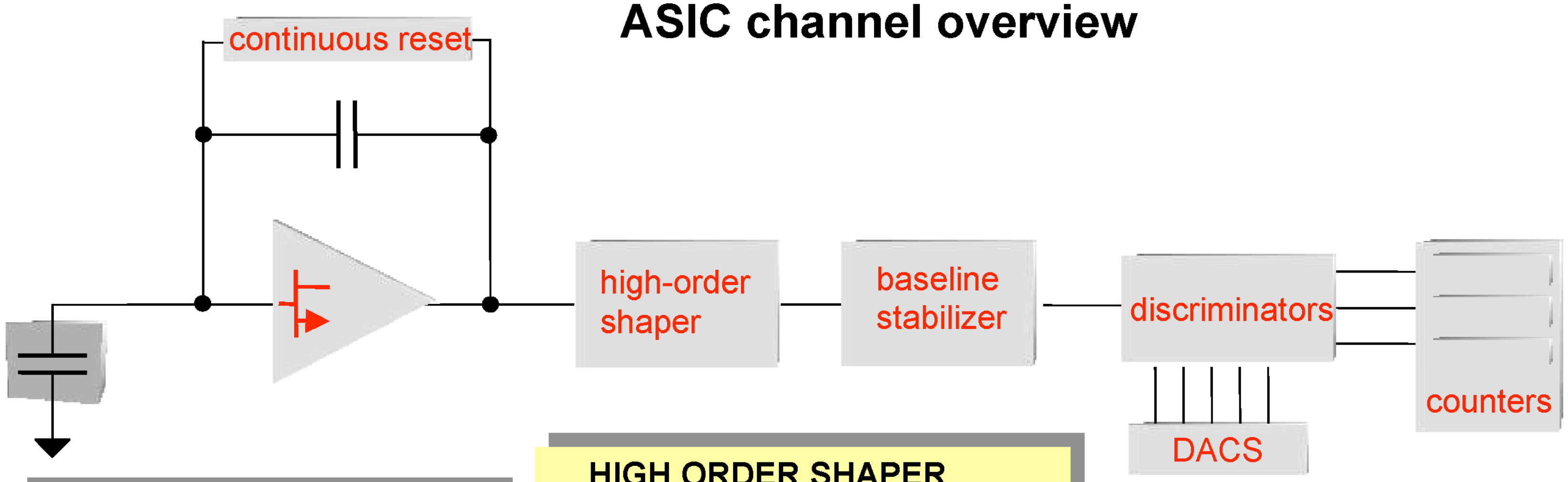
X-ray photon counting

- Provides optimal signal/noise ratio
  - = sqrt(N)
  - Detector-generated noise usually negligible
- Limited max. count rate
  - Requires dead-time correction
  - often is limiting factor on data collection speed.
- Complex readout electronics
  - proper setup requires 'expert'

Semiconductor detectors

- Use low-noise electronics to measure charge produced by individual x-ray photon, rather than average current produced by many photons.
- Challenging electronics design
  - each 10keV photon generates ~3000 electrons (0.5fC)
  - 150eV -> ~40 electrons. This requires very low noise amplifiers which contribute negligibly on this scale. State-of the art detectors achive this.

ASIC channel overview



INPUT p-MOSFET

- optimized for operating region
- NIM A480, p.713

CONTINUOUS RESET

- feedback MOSFET
- self adaptive 1pA - 100pA
- low noise < 3.5e$^-$ rms @ 1μs
- highly linear < 0.2% FS
- US patent 5,793,254
- NIM A421, p.322
- TNS 47, p.1458

≈ 3 mW

HIGH ORDER SHAPER

- amplifier with passive feedback
- 5th order complex semigaussian
- 2.6x better resolution vs 2nd order
- TNS 47, p.1857

BASELINE STABILIZER (BLH)

- low-frequency feedback, BGR
- slew-rate limited follower
- DC and high-rate stabilization
- dispersion < 3mV rms
- stability <2mV rms @ rt×tp<0.1
- TNS 47, p.818

DISCRIMINATORS

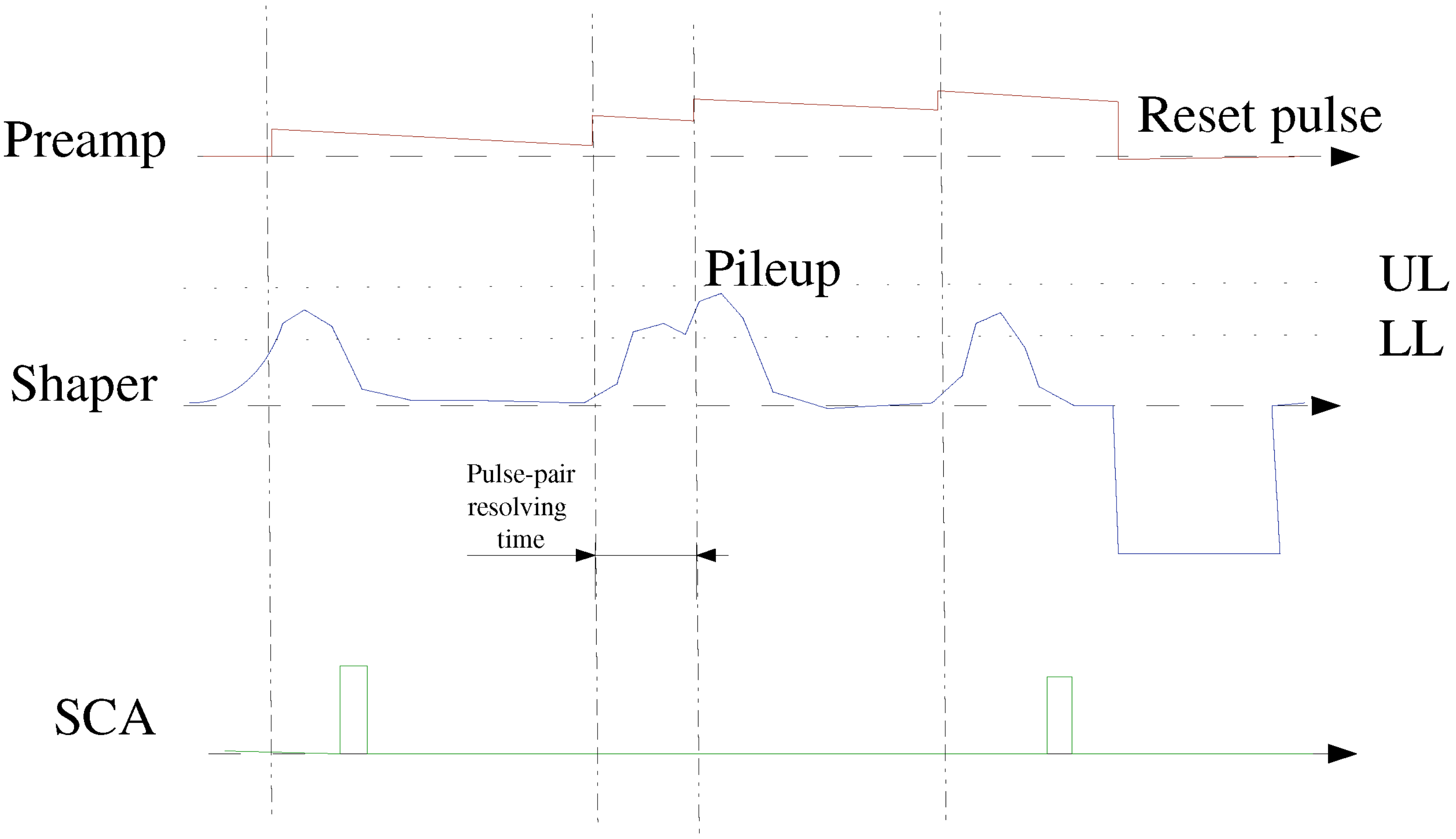
- five comparators
- 1 threshold + 2 windows
- four 6-bit DACs (1.6mV step)
- dispersion (adj) < 2.5e$^-$ rms

COUNTERS

- three (one per discriminator)
- 24-bit each

≈ 5 mW

Signal processing

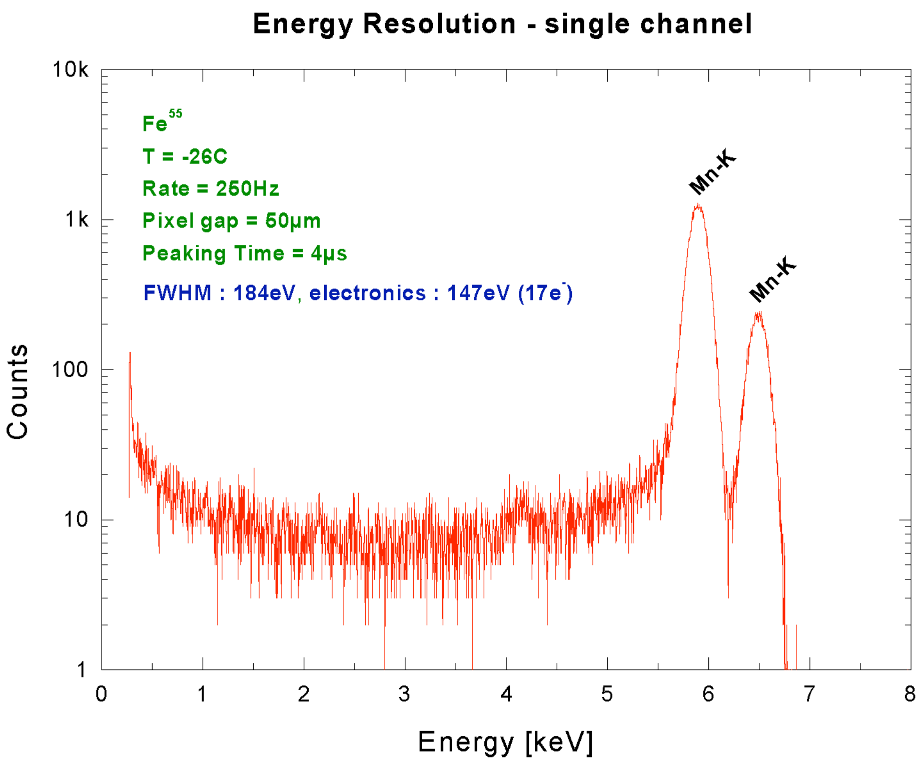


Dead time

- Period of time when detector cannot count photons
  - During single photon processing
  - During pile-up events
  - During detector preamp reset
  - Causes aparent non-linearity in measured intensity
- Must be made negligible or corrected for
  - simplest correction for first term is Nr=No/(1-No*Tau)
    - Nr = real counts; No = observed counts; Tau = dead-time per photon
    - Tau must be determined experimentally.
  - Some hardware can make corrections on the fly.

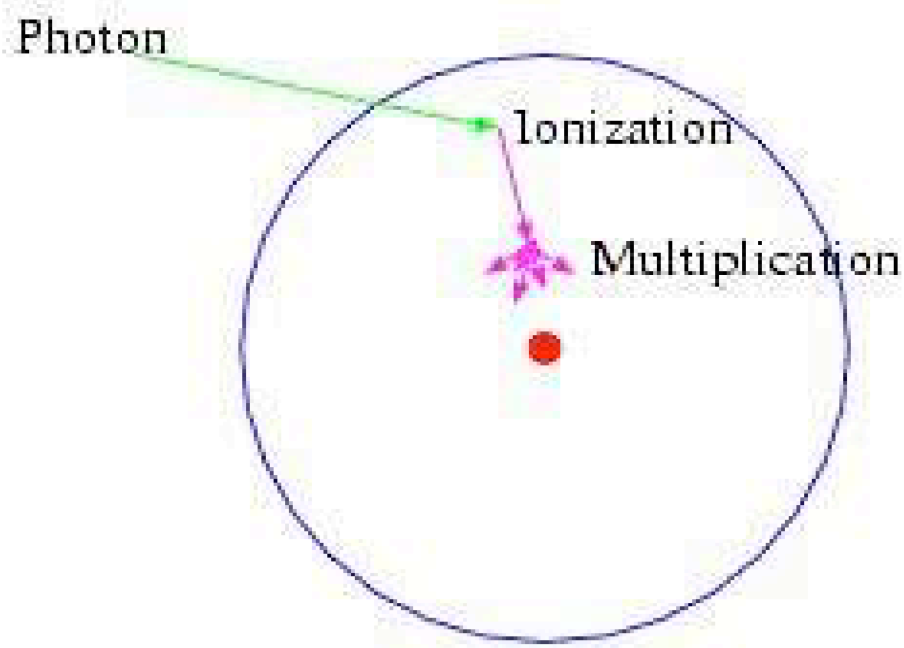
Typical spectrum for Mn K emission

- Resolution sufficient to resolve alpha and beta
- Low-energy tail always present to some degree
- Typical real sample spectrum is much more complex than this
  - Elastic scatter from probe beam
  - Escape peaks
  - fluorescence peaks from other elements
  - Compton scattering



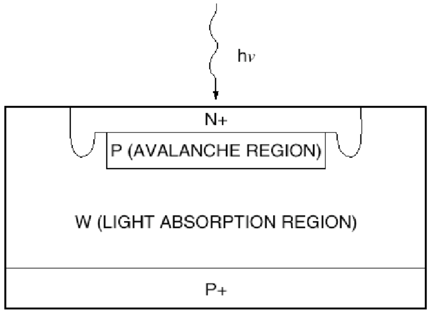
Proportional counters

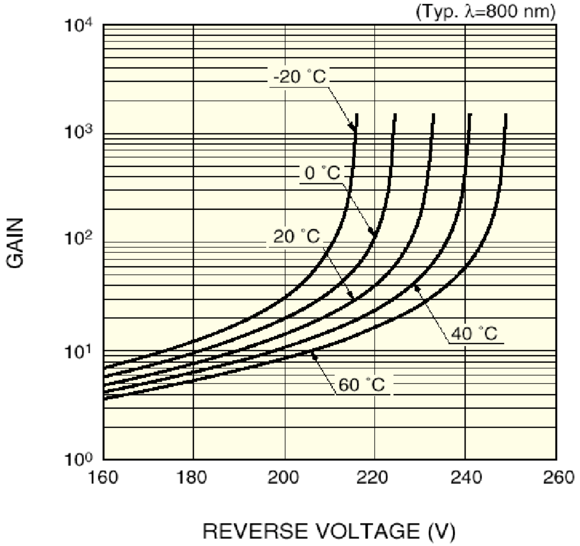
- Uses controlled avalanche multiplication of electrons in a gas
- Avalanche occurs in high-field region near center thin wire
- Charge is collected and processed like Ge detector
- Energy resolution is 10-20% (compared to 1% for Ge detector)
- Can be fast (~1MHz)
- Can make multiwire and position-sensitive.
- Not used for EXAFS?

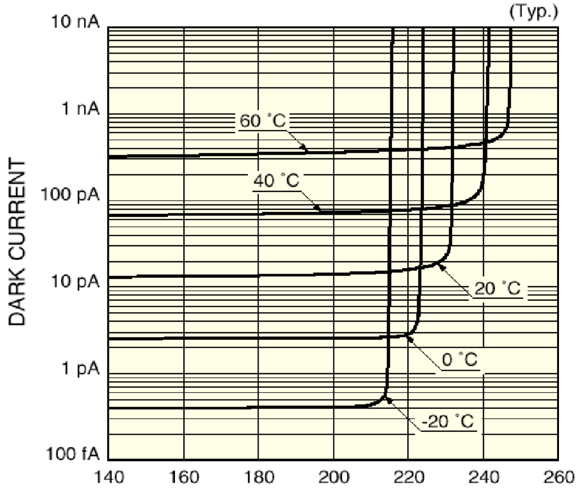


Avalanche photodiodes for x-ray detection

- Use special doping profile to create high-field region in a reverse-biased silicon diode.
- Energetic collisions of photo-generated carriers produces carrier multiplication.
- Device is intrinsically unstable!







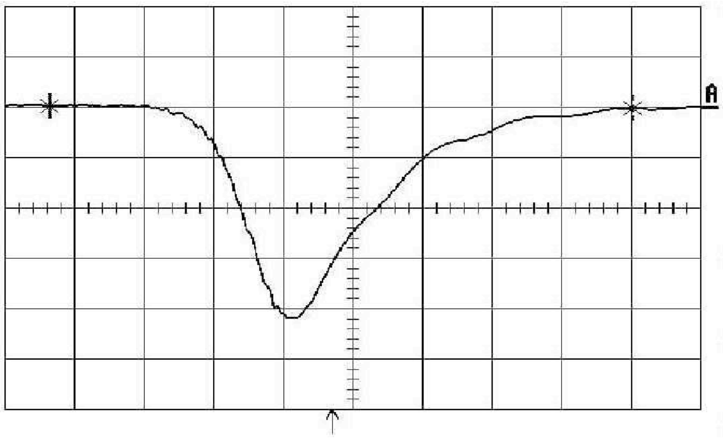
Avalanche photodiode detector for high dynamic range point counting.

- Many experiments still use NaI-phototube detectors for point-counting situations. These have a count-rate limit of around 100KHz.
- It is therefore frequently necessary to attenuate beams in order to bring the count rate into the linear range of such a detector.
- Integrating detectors have significant disadvantages and a serious noise penalty at low rates.
- Avalanche photodiodes have become quite reliable, and have capabilities above 10^7 Hz, with similar energy discrimination to NaI.
- We have adapted an existing design to make it user-proof.

APD detector head

APD Detector Head Specifications:

- Pulse height resolution ~30% up to 10 MHz (measured at 9 KeV)
- Efficiency ~ 50% (measured at 10 KeV compared to NaI)
- Maximum rate - ~10 MHz unipolar, ~100 MHz bipolar (with external circuitry)
- Rise time (10 – 90%) t_r ~ 1.8 nSec.
- Fall time ~ 5.5 nSec.
- Width (FWHM) ~ 3.8 nSec.
- Output ~ -430 mV for 9 keV X-rays with 370 V bias
- Maximum output -2.5 V into 50 W
- Diode gain @ 370 V ~ 200, amplifier gain at 100 MHz ~ 60 dB

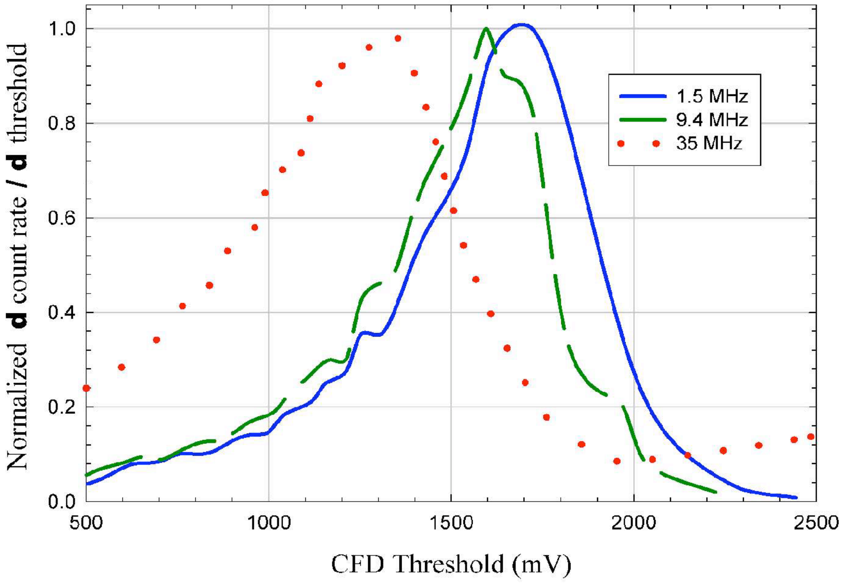


Averaged one photon output signal from APD detector head
With 9 KeV X-rays.
Horizontal = 2 nSec/Div., Vertical = 100 mV/Div.

NIM service module

NIM Module Specifications:

- **SCA / CFD**
  - **Input impedance 50 W**
  - **Timing resolution: ~ 60 pSec. (FWHM)**
  - **Input thresholds lower and upper level: 0 – -2.5 V**
  - **Fixed input delay: t_d = 2 nSec., t_d > 2/3 * t_r for true constant fraction**
  - **TTL output into 50 W**
    - **Rise time – 2.2 nSec.**
    - **Fall time – 3.5 nSec.**
    - **Width (FWHM)– 6.2 nSec.**
    - **Maximum rate ~ 100 MHz**
- **HV APD bias output 0 – 400 V**
- **HV trip point 0 – 30 mA**



Summary

- Synchrotron radiation is intense, polarized, pulsed.
- All wavelengths from IR through hard X-ray.
- Beamlines can extract highly monochromatic beams using mirrors and monochromators to tailor the properties of the radiation.
- A wide range of detectors exists. Each experiment should consider what its optimum set should be.
- Detectors will lie if you don't treat them properly.